THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

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SOME ASPECTS OF THE J PHENOMENON

TOGETHER WITH

AN ACCOUNT OF SOME MEASUREMENTS ON THE RANGES OF α-PARTICLES

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PART I

SOME ASPECTS OF THE J-PHENOMENON

General

During the course of some experiments to determine the relation between the energy of the K characteristic X-radiation emitted by an element and the number of electrons in the K corpuscular radiation associated with that particular characteristic radiation, Barkla observed a sudden unexpected increase in the ionization in air at a frequency greater than the K frequency for air. This result suggested the existence of a J characteristic radiation which was supported by other observations. When a primary X-radiation of increasing penetrating power (obtained by hardening a gas-filled tube) was passed through an absorbing substance, the absorption as usually measured steadily decreased but at one stage - certainly in one region- there was observed:-

1. A sudden increase in the absorption of the primary beam.
2. An increase in the ionisation of a gas or an increase in the electronic emission from a solid.
3. The emission by the absorber of a secondary radiation more absorbable than the primary.

These effects supported the theory of a J characteristic radiation but/this explanation of the J-phenomenon was untenable in the generally accepted sense was shown by the following observations:-

1. The phenomenon did not always occur or was conditional on some unidentified factors and not on Stoke's Law.

2. The increase in the absorption of the heterogenous beam due to the excitation of K or L characteristic radiation took place less suddenly than that due to the J absorption. It appeared as if, in the latter case, the absorbing property of a substance suddenly changed for all the constituents of the radiation at the same time and then continued normally in the new state.

3. The point at which the discontinuity occurred apparently was connected with the absorption coefficient and not with the wave length.

4. The change with atomic number in the penetrating power of the radiation for critical absorption was small.

Experiments were next carried out using scattered radiations. The J-phenomenon appeared for long periods and it seemed as if scattered radiation was more favourable to its occurrence than primary.

The absorbability or absorption coefficient of a substance in all experiments on the J-phenomenon is defined as the mean mass absorption coefficient μ/ρ given by the equation

$$I = I_0 e^{-(\mu/\rho)\rho x}$$

where I_0 is the intensity of the incident beam, I the intensity of the emergent beam, x the thickness of the absorber and ρ its density, intensity being measured by ionization. The quantity μ/ρ is measured in all cases for about a 50% decrease in intensity, the absorber being aluminium in all cases in which the substance is not specifically

mentioned.

In the early experiments the absorbability of the rays in two substances was measured as the tube was hardened and the discontinuity was observed in the ratio of the absorbabilities. Plotting corresponding readings of absorption coefficients two distinct levels were obtained as shown in Fig. 1

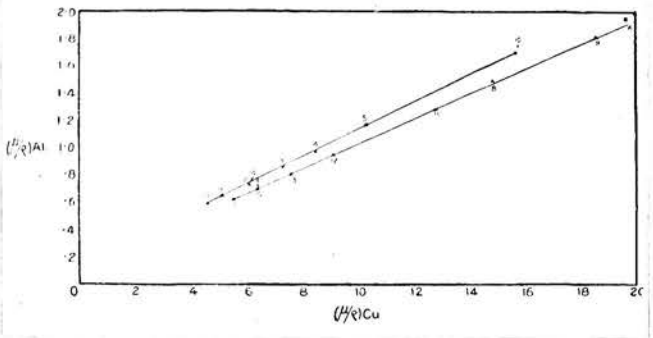


Fig. 1.

In some experiments only one level was obtained and in others the values appeared to jump from one level to the other due to a sudden change in the absorbing power of one of the absorbers. Discontinuities were obtained with absorbers of carbon, nitrogen, oxygen, aluminium, sulphur, copper, platinum, gold and lead.

Further evidence was now obtained for the dependence of the J discontinuities (two at least being known) on the absorbability of the radiation and not on

the presence of any definite wave length or of any special type of radiation. The discontinuities appeared in primary beams, where a narrow pencil of heterogeneous unpolarised intense radiation was used, in scattered beams where a wide pencil of heterogeneous highly polarised feeble radiation was used, and also in beams consisting mainly of characteristic radiation. Further, if an unfiltered primary radiation gave no indication of the phenomenon, on filtering by a thin sheet of copper or some other substance, the discontinuity appeared. Beams from the same tube but in different directions and therefore differing in penetrating power, each showed a discontinuity at the same value of the absorption coefficient. Again if scattered radiation was used, the discontinuity appeared at the same value of (μ/ρ) whatever was the thickness of the scatterer. If the beam was filtered first with aluminium and then with copper, discontinuities appropriate to both absorbers were obtained.

In all the experiments already mentioned, the amount of filtering substance was kept constant and the penetrating power of the radiation varied. Experiments were now made in which successive sheets of filtering substance were placed in a heterogeneous beam and the absorbability of the emergent beam was plotted against the percentage reduction in ionisation as a measure of the percentage previously absorbed by the filtering substance. It was then realised

that the discontinuity was brought about by the last absorbing sheets by which the absorption coefficient was measured.

In the experiments of Barkla and Khastgir the intensities of a primary beam P and a scattered beam S were compared, the ratios of both S/P (unfiltered) and S'/P' (both beams filtered by the same thickness of absorbing substance) were plotted against the absorption coefficient of the scattered beam, the penetrating power of the radiation being progressively increased. Experiments were also made when, instead of varying the hardness of the tube, the thickness of the filters was increased step by step. In these cases sudden changes in the value of the ratio sometimes occurred and always at definite values of the absorbability.

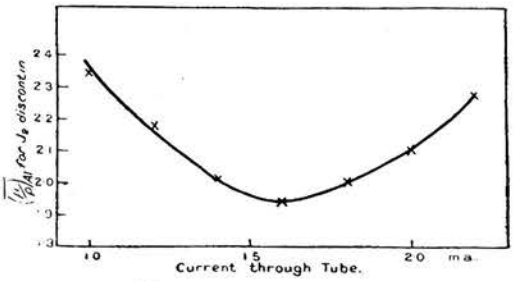
In conjunction with Professor Barkla I now carried out experiments to be described later in detail, using two beams of X-radiation scattered at different angles to the primary. Equal sheets of absorbing material were placed in each beam, their thickness being progressively increased. The ratio of the ionisations produced by the two beams for different thicknesses of the absorbers was measured and plotted against the thickness of the absorber. The ratio remained constant except for sudden changes indicating a J absorption in one beam, and these discontinuities occurred at the same value of the absorbability for that beam as had previously been obtained.

In some of the experiments already discussed

no discontinuities were obtained and no explanation could be given of their occurrence or non-occurrence. The X-ray tubes used were of the gas filled type run by induction coils and mercury breaks. I now found that by altering the frequency of the break, one type of curve - that with discontinuity, could be made to merge slowly into the other type - that without discontinuity. It thus appeared that the occurrence of the J-phenomenon depends on the conditions of excitation of the tube. As further important results have been obtained since this work was carried out, it will be found convenient to summarise them before proceeding to the details of my own experiments.

Watson found much greater regularity in the occurrence of the J-phenomenon using a Coolidge tube with the filament current and the applied potential carefully regulated. He studied the radiation scattered from paraffin wax in a direction making an angle of 90° with the primary beam. The absorber used was aluminium and the ratio of the intensities of the secondary and primary beams for different thicknesses of the absorbers were compared. Equal absorption of the two beams occurred except for sudden changes in the absorption of the scattered beam at critical points. Previously the value of the absorbability at the J discontinuities had been found remarkably, though not absolutely, constant, but now, on varying the current through the tube, a systematic variation of

the absorbability was obtained for each observed discontinuity (Fig. 2).



Mo target: 40 kv. peak.

Fig. 2.

Experiments were also made with the absorbers at different distances from the anticathode and the current through the tube was kept constant. The critical absorbabilities were not affected, thus showing that the variation obtained before was not merely due to a change in the energy density of the radiation. Further with a given current, a variation of the potential applied to the tube produced no change in the critical absorbabilities. It was thus concluded that the critical absorbability depends on the total measure of the stream of electrons striking the anticathode. From Fig. 2 it is seen that for one value of the current through the tube there is a minimum value of the critical absorbability which corresponds closely to the values found with gas filled tubes. This minimum occurs for a current of about

1.5 milliamps. No data are available on the currents used with gas filled tubes but the above current is a very likely value. The following are the values of the absorbabilities at these minima:-

$(\mu/\rho)_{Al.}$	3.76	3.24	2.44	1.94	1.40	0.73	0.47
mean values previously obtained (mainly with gas tubes)	3.8			1.9		0.7	0.34

Further experiments by Watson show the presence of the J discontinuities with copper absorbers and also with the radiation from thin fluorescent radiators. In the latter case of almost pure characteristic radiation, the secondary radiations given off in two directions making different angles with the primary beam were compared for various angular positions of the radiator. If the radiator was nearly normal to the primary beam the ionization ratio remained practically constant when increasing equal thicknesses of aluminium were placed in the beams. At other settings of the radiator, sudden changes in the ratio occurred due to a decrease in the ionization produced by the beam making the larger angle with the normal to the radiator.

Complete failure to find any trace of the J-phenomenon has been the result of experiments by Gaertner, Worsnop, Dunbar and Alexander. It appears probable

however that these negative results may be due to a lack of steadiness in the radiation used since Watson found extreme steadiness to be essential for the occurrence of the phenomenon.

It thus appears that the J-phenomenon may occur in primary, characteristic and scattered radiations under certain conditions not yet fully determined.

The work to be discussed in detail below deals only with the J-phenomenon in relation to scattered radiations and was carried out by me under the direction of Professor Barkla in the Physical Laboratory of Edinburgh University during the years 1924 to 1926.

APPARATUS

The X-ray tubes used were of the gas filled type and the radiation was excited by means of an induction coil and mercury jet interrupter. A primary beam from the tube was directed on to a scatterer S of paraffin wax or aluminium situated as shown in Fig. 3. In this diagram the full heavy lines indicate the positions of lead screens.

The two scattered beams proceeding in directions making angles of approximately 60° and 120° with the direction of the primary beam were received and measured by the two similar gold leaf electroscopes E_1 and E_2. Absorbing sheets of Aluminium of equal

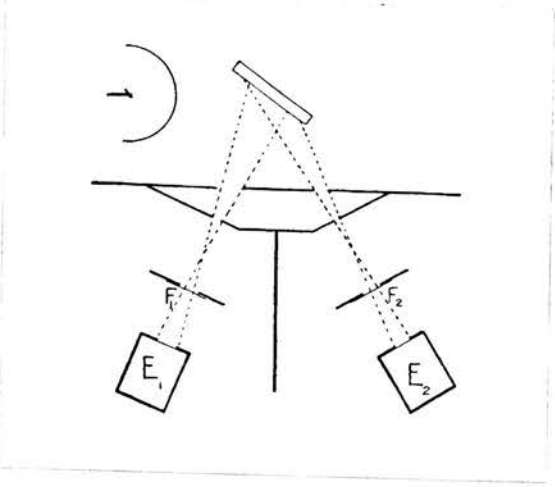


Fig. 3.

thickness could be placed at F_1 and F_2 the two secondary beams thus being intercepted in the same way. As the thickness of these absorbing sheets was gradually increased by small steps, any difference in the absorbability of the radiations could be observed by measuring the ratio of the ionizations produced in the electroscopes. If the two beams were exactly similar, then similar absorbing sheets should affect them in the same way and the ratio of the ionizations should remain constant. A change in the ratio would indicate any difference in the constitution of the two beams.

Unless the primary beam was really homogeneous a difference in the constitution of the two beams might arise from unequal filtering by the scatterer itself. This however is easily eliminated, as in the experiments of Barkla and Ayres on the distribution of scattered

radiation, by arranging that the scattered beams studied should make equal angles with the normal to the scattering plate, and pass through equal thicknesses of that plate, as was arranged in the later experiments. The precaution is unnecessary if either a very thin or a very thick sheet of scattering substance is used. It is unnecessary too in a substance consisting of very light atoms, for here there is very little selection of the constituent radiations, the absorption of the different constituents varying only slightly with the wave length of the radiation; such a substance is paraffin wax. Consequently in these earlier experiments with paraffin wax and even with aluminium as scattering substances, there was little effect due to the difference of obliquity of the two scattered beams.

In order to make the conditions as simple as possible and to remove the possibility of an effect due to different absorption of the two beams in the scatterer itself, it was later arranged that the two directions of the scattered radiations tested should make the same angle with the normal to the scatterer, and so pass through equal thicknesses of absorbing substances, as do the beams entering electroscopes E_0 and E_1 in Fig. 4. Similar results were obtained with the two different arrangements of the apparatus, in the later experiments the electroscope E_0 acting

in the same way as the electroscope E_2 in the earlier work.

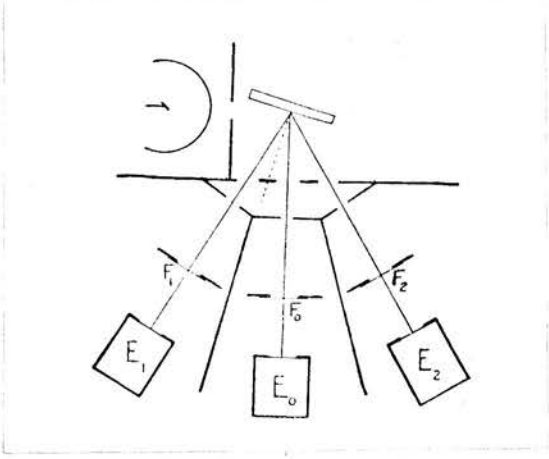


Fig. 4.

RESULTS

A representative series of results is shown in Fig. 5, the ratio of the ionizations I_1/I_2 produced in the two electroscopes E_1 and E_2 as equal and increasing thicknesses of aluminium are placed in the two beams being plotted against the thickness of the absorbing aluminium.

The remarkable features shown in these results are the following:-

1. In the complete series of fifteen experiments, fourteen exhibit no difference between the absorption of the two scattered beams except at the J discontinuities. This is shown by the horizontality of the lines indicating that one beam is absorbed exactly as the other. At the J discontinuities a sudden

change of about 7.5% occured in the ratio of the ionizations when aluminium was used as the scatterer, and of about 10% in the case of a paraffin wax scatterer. In some of these experiments as much as 75% of the total ionization was cut off between the J_1 and J_2 discontinuities, so that the constancy of the ratio was tested over a wide range.

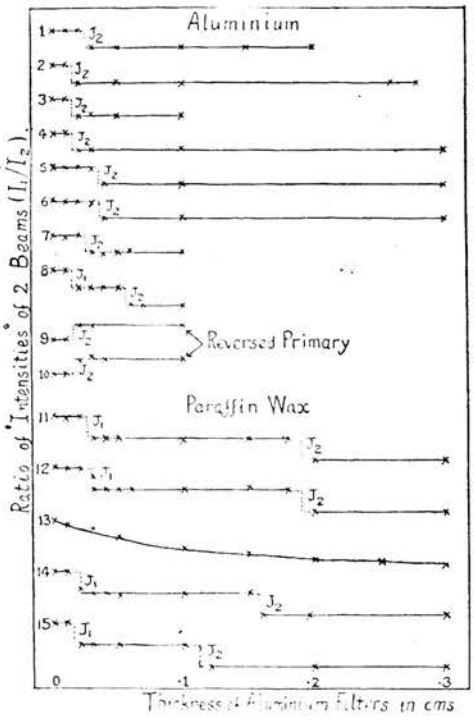


Fig 5.

2. The J discontinuities were shown by one scattered beam and not by the other, the beam showing the discontinuities being that at an angle of 120° with the primary. This was proved by taking a set of measurements on each beam separately. When the direction of the primary was reversed, i.e. the X-ray tube was placed on the other side of the scatterer everything else remaining unchanged, then the electroscope E_2 received the beam showing the discontinuity. In these experiments (9 and 10) the ratio I_1/I_2 as previously measured suddenly rose at the discontinuity. This result shows that the occurrence of the discontinuity in the beam at an angle of 120° with the primary was not due to any peculiarity of situation or configuration, except with regard to the primary beam. In his experiments on the J-phenomenon in fluorescent radiation, Watson observed that the discontinuity occurred in the secondary beam which made the greater angle with the normal to the radiator, if both scattered beams were at the same angle to the primary, the radiator being rotated. But it was also observed that a discontinuity occurred with the radiator normal to the primary beam on increasing one of the angles at which the secondary radiation was observed, and the beam now making the greater angle with the normal to the radiator and the direction of the primary showed the discontinuity. This latter result is in agreement with my results obtained for scattered radiation.

The values of the absorption coefficient ( ) calculated from a 50% "absorption" of the beam which gave the discontinuity agree remarkably well with those obtained for beams of various kinds as may be seen in Table I.

TABLE I.

Number of Experiment.	Scattering Substance.	Thickness of Scatterer.	"Absorption Coefficients" of Unintercepted Radiations $\left(\frac{\mu}{\rho}\right)_{Al}$	"Absorption Coefficients" at J Discontinuities. $\left(\frac{\mu}{\rho}\right)_{Al} J_1$.	$\left(\frac{\mu}{\rho}\right)_{Al} J_2$.	$\left(\frac{\mu}{\rho}\right)_{Al} J_3$.
1	Aluminium	1·9 cm.	2·8	...	1·85	
2	„	„	2·5	...	1·9	·71
3	„	„	2·5	...	2	
4	„	„	2·6	...	2·1	
5	„	·6 cm.	3·4	...	2·1	
6	„	·3 cm.	3·5	...	2·1	
7	„	1·9 cm.	3·0	...	1·95	
8	„	·3 cm.	4·0	3·6	1·9	
9	„	„	2·6	...	2	
10	„	„	2·6	...	2	
11	Paraffin Wax	1·7 cm.	4·3	3·6	1·9	
12	„	„	4·5	3·6	2	·75
13	„	„	4·4			
14	„	„	4·3	3·7	2	
15	„	·7 cm.	4·6	3·6	2	·8
Mean of all experiments				3·6	2	·75
Mean of values obtained by earlier workers.				3·8	1·9	·7
Minimum values obtained by Watson.				3·76	1·99	·73

In some of my experiments three discontinuities were obtained by filtering one complex radiation, the three discontinuities appearing one after another in the appropriate positions. The results of these more extensive series of

filtering experiments are shown in Fig.6. Thus although the two beams from paraffin wax for example were usually absorbed at the same rate, the beam making an angle of 120° with the primary showed three sudden falls in ionizing power when the values of the absorbability were 3.6, 2.0 and 0.75, and the ionizing action of the beam was cut down in all by about 27% relative to the beam scattered at 60°. It seems probable that if the filtering could have been carried further, the J_4 and J_5 discontinuities would also have occurred.

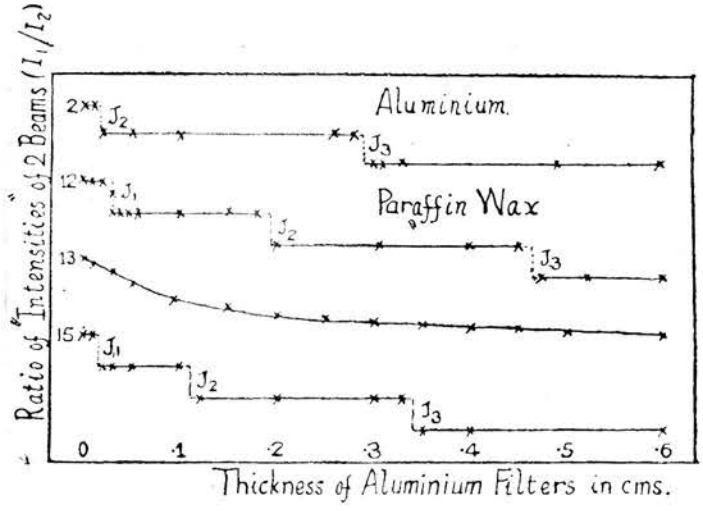


Fig. 6.

When the primary beam was "softened", the filtering had to proceed a little further before the critical absorbability was reached, when "hardened" the discontinuity

occurred earlier in the filtering process. This is seen by a comparison of the discontinuities in Fig. 5 with the corresponding absorption coefficients of the unintercepted beams given in column 4 of Table I. The position of the discontinuities was thus under control.

THE SUPERPOSITION OF TWO BEAMS OF X-RAYS :

That the J absorption and all the associated phenomena depend on the whole of a complex beam and not on any of its components, is shown most directly by the following experiments. A thin sheet of scattering aluminium was placed in position as before, and the thickness of filtering aluminium at which the J discontinuity occurred was found. When a thicker sheet of scattering substance was placed behind the first so that there was superposed on the radiation X previously experimented upon a more penetrating radiation Y

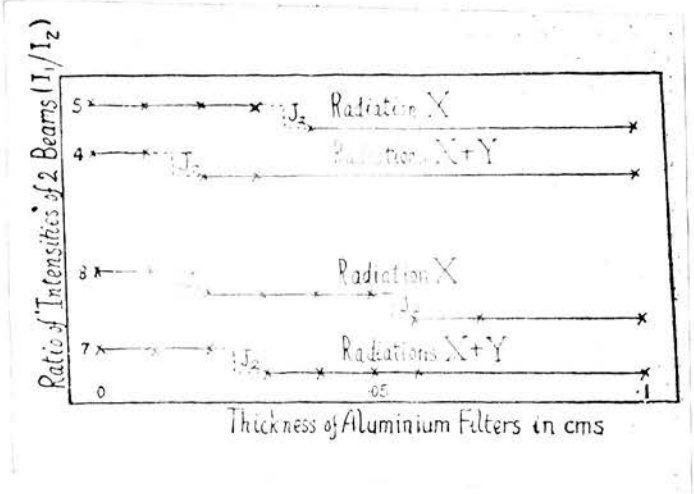


Fig 7.

from deeper layers, it was found that the first discontinuity

had moved to a thickness of filtering aluminium appropriate to the complex beam as a whole.

Thus experiment 5, Fig. 7, was made with a scattering sheet of aluminium 0.6 cm. in thickness, and showed the J discontinuity at a thickness of filtering aluminium between 0.03 and 0.04 cm; whereas, when the thickness of scattering aluminium was increased to 1.9 cm. and the ionization in the electroscope was roughly doubled, the J discontinuity occurred for a thickness of filtering aluminium between 0.01 and 0.02 cm. (Experiment 4, Fig. 7). In order to avoid any possible effect due to a change in the primary radiation, the readings with the two thicknesses of scattering substance were taken in alternate pairs, so that corresponding points were obtained with practically identical radiations. A similar method was adopted in experiments 8 and 7, the thinner scattering sheet (experiment 8) being reduced to 0.3 cm. thickness. The scattered beam was now sufficiently soft to show the J_1 discontinuity in addition to the J_2 discontinuity. With the additional thickness of 1.6 cm. of scattering aluminium, making a total thickness of 1.9 cm. (that is in experiment 7), the J_1 discontinuity was driven out of the range of the experiment and the J_2 discontinuity was displaced from a thickness between 0.05 and 0.06 cm. to between 0.02 and 0.03 cm.

These experiments show directly the

coherence of constituent radiations, or in other words that the J-phenomenon is independent of individual harmonic constituents of a radiation but dependent on the beam as a whole. This effect of the superposition of two beams has been demonstrated even more conclusively by the experiments since carried out by Barkla and Sen Gupta. In these later experiments the two superposed beams X and Y came from widely separated scatterers illuminated by the same primary beam. The secondary radiations from these two scatterers were observed in directions making an angle of about 45° with one another and the two beams crossed only at and near the absorbing sheets thereafter separating again so that the intensities of the two beams (measured by an ionisation effect), could be observed independently. It was found that the two beams were still coherent during their passage through the absorber. The transmission of Y through the absorbing aluminium affected the absorption of X and the J discontinuity present was displaced in the same manner as in my experiments. Thus we are led to the conclusion that the absorbing properties of aluminium depend not only on the radiation of which the absorption is being measured, but on the total radiation passing through the absorber and the radiation passing through an absorber is to be considered as a whole and not as a number of independent constituents.

THE TWO TYPES OF ABSORPTION :-

The results of my experiments lead to two separate cases in the absorption of scattered radiation namely case (a) in which the difference between the scattered beams is shown only by the discontinuities in the absorption of the beam scattered at 120° and case (b) illustrated by experiment 15, in which the two beams differ continuously in absorbability. Many results of both types were obtained. In case (a) as the beams were transmitted through aluminium, and by filtering reached greater and greater average penetrating powers, there appeared three strongly marked "absorption lines" in the beam at 120°, but not in the beam at 60°. In case (b) instead of showing "absorption lines" the beam at 120° was continuously more absorbable than that at 60°.

These results are indicated in Figs. 8 and 9. In fig. 8 ionization is plotted against thickness

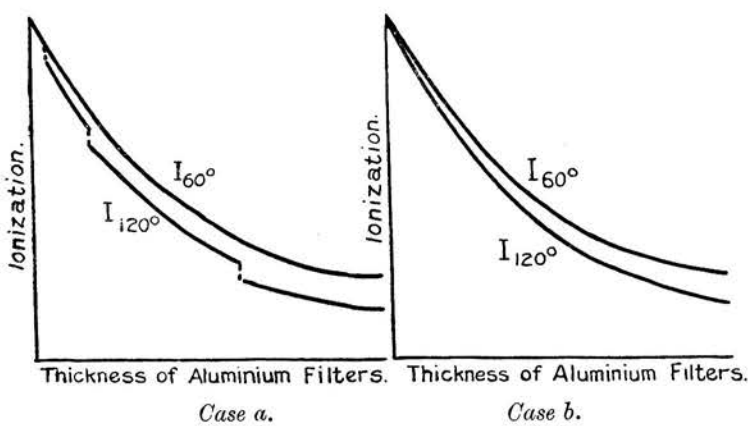


Fig. 8.

of absorbing aluminium, $I_{120}o$ showing the steps, $I_{60}o$ showing steadily decreasing intensity in case (a). In the alternative case, case (b), neither beam showed any discontinuity by successive filtering, but $I_{120}o$ fell more rapidly than $I_{60}o$, that is the former was more absorbable. In Fig. 9 absorption coefficients calculated as previously indicated are plotted against the thickness of aluminium, the beam at 120° showing the peaks, but that at 60° giving a smooth curve in case (a). The other case is shown on the right side of the figure with no unusual features, but the beam at 120° has a steadily higher absorption coefficient.

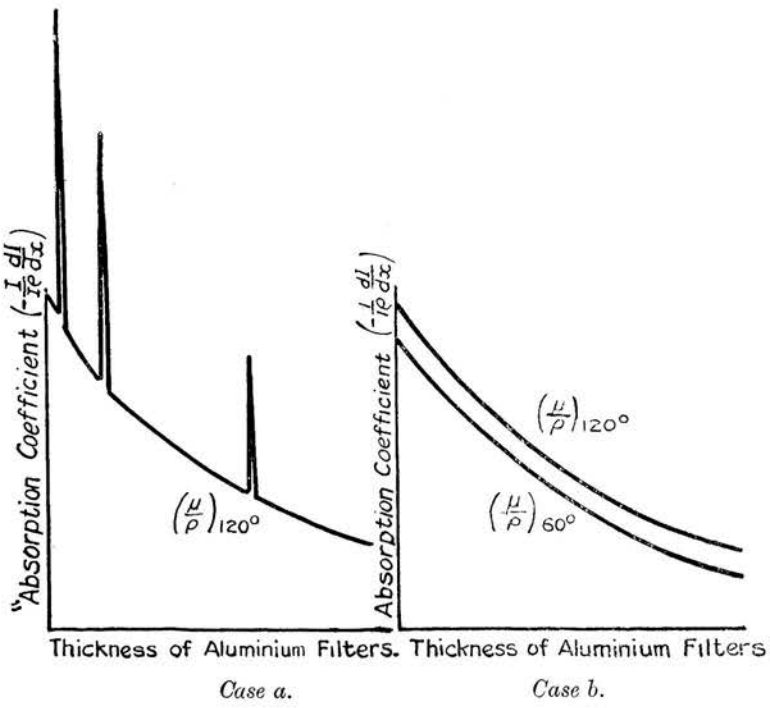


Fig. 9.

At the time of these experiments there was no indication of the cause of the difference between the two results, or of the factors which determined whether the result of an experiment should be (a) or (b). It had however, been made clear that these were of a nature never previously taken into consideration, and that the distinctive feature was the dependence on some sort of average constitution of the whole heterogeneous beam, and not on any particular constituent frequency, or even a simple combination of frequencies. A systematic search for the cause of the variable result showed at once that it depended on the details of the process of excitation of the X-rays. The X-ray tube was excited by an induction coil with mercury jet interrupter. The frequency of interruption of the primary current was varied, and experiments were performed in the manner previously described. Fig. 10 illustrates the type of results obtained, the ratio of $I_{120°} / I_{60°}$ being plotted against the thickness of absorbing aluminium for frequencies of interruption varying from 79 to 109 per second. It is seen that as the frequency of interruption alters, case (a), showing discontinuities, gradually merges into case (b), showing a steady difference of absorbability. More precisely case (a) was produced at only a very definite frequency of interruption, or over a very narrow range of

frequencies, a frequency 97 per second showing the most abrupt change in ionization. With lower and higher frequencies the width of the "absorption line" increased rapidly until it spread through the whole of the absorbability range, and case (a) had become case (b). Each complete set of these curves was taken in a day and on returning at any stage to a break speed of 97 per second the discontinuity appeared sharply. Series of curves similar to that shown in Fig. 10 were obtained at intervals over a period of about a

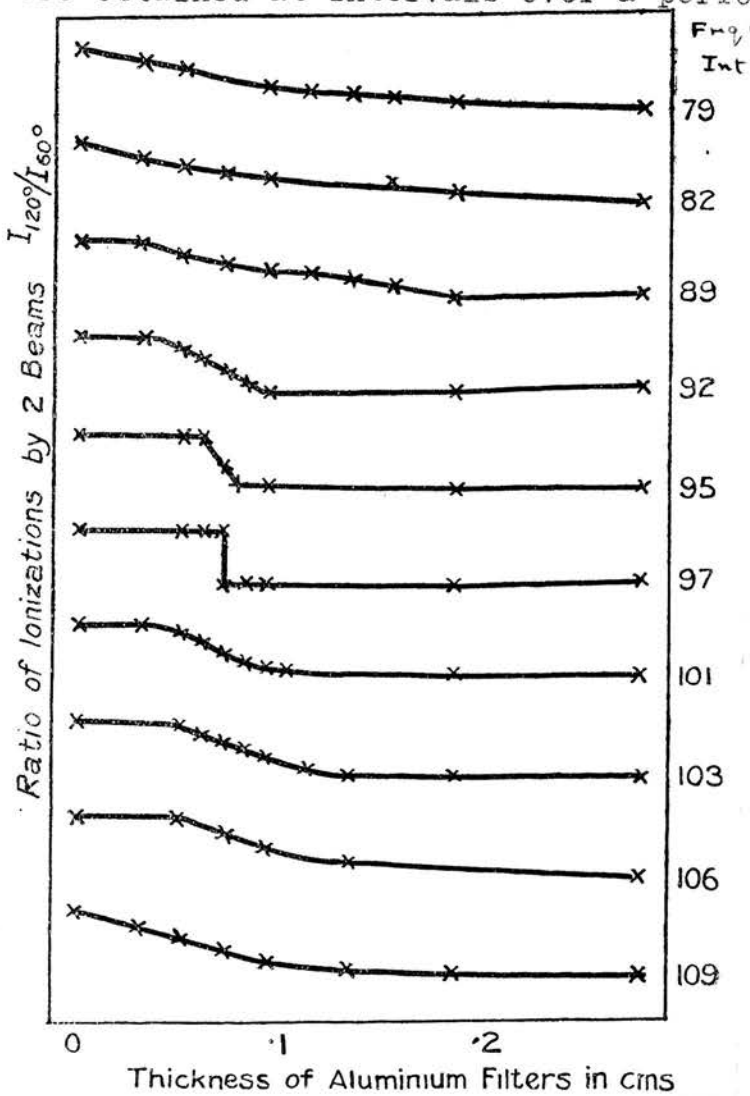


Fig. 10.

fortnight. But the frequency of the interrupter is not the fundamental factor. With a different X-ray tube the critical frequency was not 97 but was considerably over 100, and later still, after many alterations, only case (b) appeared throughout the whole range of frequencies, as is shown in Fig. 11, obtained with the same tube. It thus appeared that cases (a) and (b) were only widely separated forms of exactly the same phenomenon and that the factor which decides the degree of activity due to a complex beam acting as a whole is to be found in the details of the method of excitation of the X-rays.

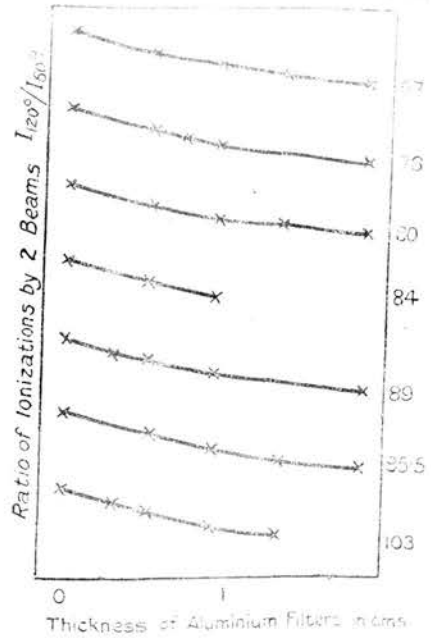


Fig. 11.

Watson working with an alternator-transformer and Coolidge tube has also found this change in the type of absorption from case (a) to case (b). The steady reoccurrence of results of the (a) type took place only when his X-ray tube was run into a steady state. If readings were taken before this state was attained there was a spreading out of the discontinuities, the curves obtained tending to the (b) type and being in general intermediate between (a) and (b). The discontinuities only appear when the conditions become sufficiently steady. In the case of experiments with gas filled tubes run by induction coils and mercury breaks there is not sufficient control of the conditions to test whether results not of the (a) type are due to unsteadiness in the running of the tube. This might easily occur and would give a satisfactory correlation with Watson's results. It might also be inferred that an induction coil runs with greatest steadiness for some definite speed of the mercury interrupter, but if this is so the optimum speed depends on the load on the secondary.

CONCLUSION

The results obtained in the experiments here described fit into the general scheme of results obtained by workers on the J-phenomenon. The discontinuities appear at the same values of the critical absorption

coefficients in aluminium as were found both before and since these experiments were performed. the magnitude of the sudden change in the ionization ratio is of the same order as that obtained in other experiments.

The principal advances made in these experiments are the following:-

(1) It was conclusively proved that the position of a J discontinuity depends on the absorption coefficient of the beam as a whole and is not occasioned by the presence of any constituent radiation or radiations;it always occurs at a thickness of the absorbing substance sufficient to reduce the hete neterogeneous beam to the critical average absorbability associated with the discontinuity, to a close approximation at least. Thus the discontinuities found in the absorption of a heterogeneous beam obtained by the superposition of radiations are definitely displaced to a position appropriate to the absorbability of the beam as a whole when the constituent radiations are varied. It appears that in the passage of X rays through an absorber there is a "coherence" of superposed radiations and that it must therefore be assumed that there is no simple law of addition of the harmonic components of a beam during its passage through matter.

(2) The greater absorbability of radiation scattered at 120° over that at 60° (which is to be expected from Compton's theory of scattering) is not always apparent from a single absorption measurement done on each beam. In certain

experiments the difference in absorbability only appeared after the thickness of the absorber had exceeded certain critical values; in other experiments the difference was apparent for all thicknesses. It was sometimes possible by controlling the conditions governing the excitation of the primary beam to produce either form of absorption (and intermediate forms) at will.

(3) The J discontinuities may by a slight controllable change in the conditions of excitation of the primary beam be made less and less sharp until finally a continuous change in the absorbability is obtained, the resultant (smoothed over) change being the same in all cases. Presumably the conditions suitable to the case of continuous change are operative in the majority of scattering experiments, in which the J discontinuities are not observed.

(4) In the experiments on scattering at 60° and 120° a simple reversal in the direction of the primary radiation (corresponding to an interchange of the two scattered beams) without any other alteration in the apparatus occasioned an interchange of the beam showing the discontinuity, it now being present in the beam previously at 120° to the primary. This shows that the factors governing the appearance or non-appearance of the J discontinuities in these experiments are (a) the angle of scattering and (b) certain conditions governing the excitation of the primary radiation, and not the design of the apparatus.

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Part II.

Measurements on the Ranges of α-Particles.

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(Communicated by Sir Ernest Rutherford, P.R.S.—Received January 21, 1930.)

Introduction.

Measurements of the stopping power of a gas relative to air, which will be defined as the ratio of the range of an α-particle in air to the range in the gas, have been made by T. S. Taylor and van der Merwe,* the former using a scintillation method for α-particles from radium C′ and polonium, the latter a Wilson chamber method for polonium only. These two methods did not give accurate results, owing, in both cases, to the difficulty in determining the range to a high degree of precision. Experiments have recently been carried out by Joliot and Onoda† to obtain an accurate Bragg curve for the α-particles from polonium in hydrogen, and by Onoda‡ in oxygen. Estimating the extrapolated range as defined by Henderson,§ they have then calculated the stopping powers of these gases using the value of the range in air given by I. Curie.‖

In the experiments to be described, the extrapolated ranges have been measured for α-particles from radium C′, thorium C, thorium C′ and polonium in air, oxygen, nitrogen, argon and hydrogen, only the portion of the Bragg curve from the maximum to the end of the range being experimentally determined. In obtaining this portion of the Bragg curve the distance of the source from the ionisation chamber was varied, the pressure being kept constant during one set of observations.

Apparatus.

The apparatus employed is shown to scale in fig. 1. It consists of a brass cylinder about 50 cm. long, at one end of which is the ionisation chamber I, resembling that used by Geiger¶ in his determination of the range of α-particles from radium C′. The parallel plate electrodes P_1, P_2 and P_3 are placed perpendicular to the path of the rays. P_1 is a brass disc connected to a quadrant

* Taylor, 'Phil. Mag.,' vol. 26, p. 402 (1913); v. d. Merwe, 'Phil. Mag.,' vol. 45, p. 379 (1923).

† 'J. Physique,' vol. 9, p. 175 (1928).

‡ 'J. Physique,' vol. 9, p. 185 (1928).

§ 'Phil. Mag.,' vol. 42, p. 538 (1921).

‖ 'Ann. Physique,' vol. 3, p. 299 (1925).

¶ H. Geiger, 'Z. Physik,' vol. 8, p. 45 (1921).

electrometer of sensitivity 800 divisions per volt, P_2 a wire grid charged to a potential sufficient to give saturation and P_3 a second wire grid, earthed, and

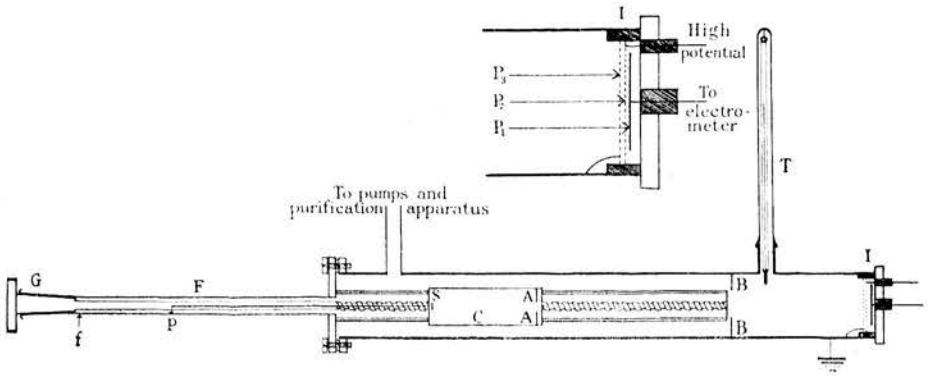

FIG. 1.

serving as a shield to prevent ions produced on the left of P_2 from entering the ionisation chamber. Ebonite insulation is used, the wire grids being held in position by ebonite rings. The separation of the electrodes P_1 and P_2 and also of P_2 and P_3 is 2 mm., and as the greatest air pressures were about 17 cm., the ionisation was measured over a fraction of less than 0·005 of the range. The ionisation chamber has a diameter of 4 cm. and the beam of α-rays is stopped down so that the entire beam enters the chamber at all distances of approach used in the measurements. The maximum difference in length of the paths of the particles before entering the ionisation chamber due to the spreading of the beam is less than the experimental error. The source of α-particles S and the slit A limiting the beam are mounted on a carriage sliding on rails. The carriage is moved by a screwed rod rotated by a ground glass joint G at the end of the glass tube F attached to the cylinder as shown. A brass rod p rigidly attached to the carriage extends into F to indicate the position of the source. The distance from the end of this pointer to a fixed mark f on the tube F was measured by a travelling microscope. A thermometer T measured the temperature inside the chamber, which could be exhausted to a pressure of 0·001 mm. The pressure of the gas was measured by a wide bore mercury manometer, the mercury levels being read by a cathetometer. The pressure was measured to an accuracy of 0·01 cm. and the temperature to 0·1° C. The pressures used were so chosen that the end portions of the ranges could be examined in the ionisation chamber and were thus different for α-particles of different ranges. At the pressures used

the α-particles from a source of activity equivalent to 1 mgm. of radium gave a maximum ionisation current of the order of 200 divisions per minute.

Gases.

The air used was dried by passing slowly over calcium chloride and phosphorus pentoxide. Hydrogen was obtained from a cylinder and was further purified by bubbling through concentrated sulphuric acid and by passing over charcoal cooled in liquid air. Oxygen was obtained by heating potassium permanganate, the gas being passed through a tube containing glass wool and then over caustic potash and phosphorus pentoxide. Cylinder nitrogen and argon were employed and were dried by passing over phosphorus pentoxide. The argon was 99 per cent. pure, the impurities being oxygen and nitrogen. It was calculated that in no case could impurities be present in sufficient quantity to affect appreciably the value of the range as measured.

Corrections for Decay of Sources.

In the case of radium C′ correction for the decay was made using the tables from "Radioaktivatät" by Meyer and Schweidler. The decay of the thorium (B + C) sources used was corrected for, taking the half value period as 10·6 hours.

Results.

A specimen curve is given in fig. 2 which shows long and short range α-particles from thorium (C + C′) in hydrogen. A list of the ranges obtained is given in Table I. The extrapolated ranges R_m were reduced to a pressure of 76 cm. of mercury and a temperature of 15° C. by the relation

$$R = R_m \times p/76 \times 288/(273 + t),$$

where p denotes the pressure used and t the temperature. In each case the value given is the mean of at least two or three determinations. The greatest deviation of any single value from the mean was less than 0·3 per cent.

Table I.

Source.	Air.	Oxygen.	Nitrogen.	Argon.	Hydrogen.
	cm.	cm.	cm.	cm.	cm.
ThC′	8·61	8·10	8·67	8·99	40·88
RaC′	6·94	6·55	6·98	7·27	32·74
ThC	4·72	4·46	4·75	5·00	21·61
Po	3·87	3·64	3·89	4·17	17·29

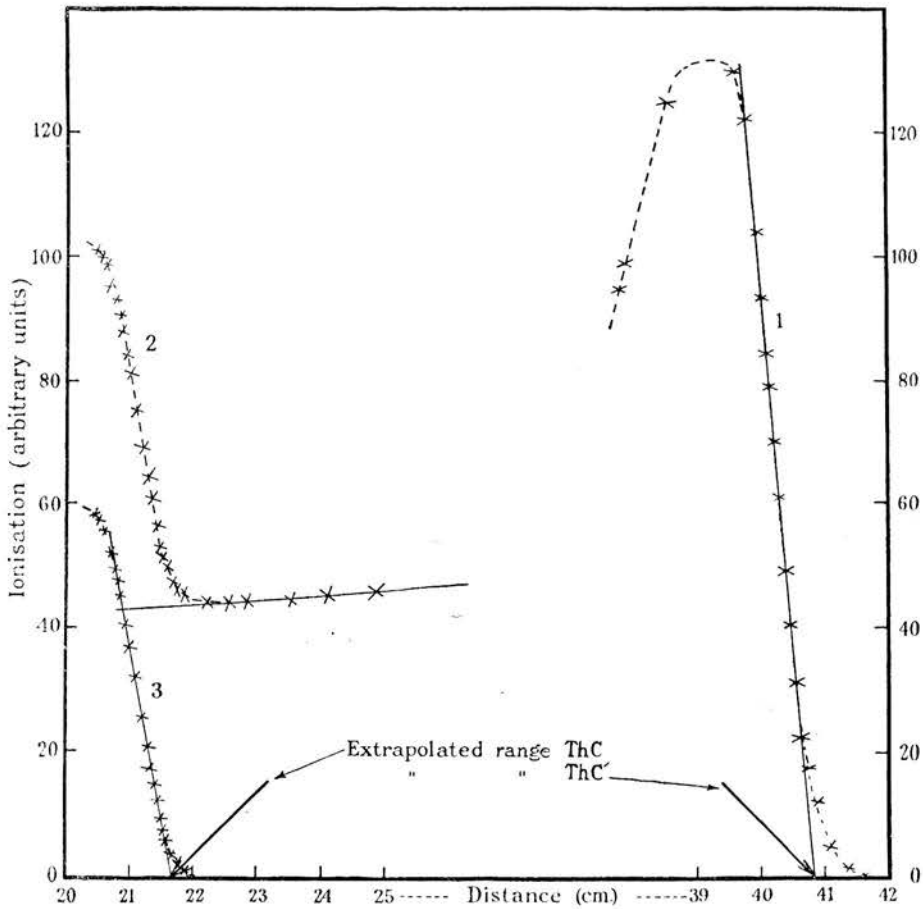

FIG. 2.—Curve 1 : ThC' α particles in Hydrogen. Curve 2 : (ThC' + ThC) α particles in Hydrogen. Curve 3 : ThC α particles in Hydrogen.

Allowing for the errors which might have been made in measurement and especially also in the drawing of the straight line portions of the curves, these values can be taken as correct to about 1 part in 500.

Some of the values obtained by other workers are given in Table II.

While the results for polonium agree very well with those of Curie, Joliot and Onoda, and Onoda, the ranges in air found for thorium C′, radium C′ and thorium C are all smaller than the values hitherto obtained. The deviation is greatest for the particles from thorium C, and in this case it seems to be definitely outside the range of experimental error. We cannot suggest any satisfactory explanation for this discrepancy in the case of thorium C. It

Table II.

Observer.*	Source.	Air.	Oxygen.	Hydrogen.
		cm.	cm.	cm.
Henderson	ThC′	8·616	—	—
Geiger	ThC′	8·617	—	—
Henderson	RaC′	6·953	—	—
Geiger	RaC′	6·971	—	—
Curie and Behounek	RaC′	6·96	—	—
Henderson	ThC	4·778	—	—
Geiger	ThC	4·783	—	—
Geiger	Po	3·925	—	—
Curie	Po	3·87	—	—
Joliot and Onoda	Po	—	—	17·30
Onoda	Po	—	3·63	—

* Curie and Behounek, 'J. Physique,' vol. 7, p. 125 (1926); and *loc. cit.*

may be noted, however, that Rosenblum† has found that the α-particles consist of four groups with different initial velocities, the main group being that of second greatest velocity. To make sure that the differences in the values were not due to some difference in the conditions of the various experiments, tests were made on the long and short range thorium particles to find if the values could be affected by any of the following alterations, viz. :—

1. The depth of the ionisation chamber P_1 P_2 approximately halved.
2. A second screen B inserted.
3. Using the maximum and minimum possible pressures.
4. Placing a mica screen in front of the source. (Geiger used a mica screen in all his measurements except in the case of radium C′.)

Further experiments were then made by varying the pressure and keeping the distance constant. The results obtained were in all cases unchanged. In case 4, it was found that the stopping power of the mica did not change sufficiently with velocity for this to affect the results. The slopes of the straight line portions of the curves for thorium C′, radium C′ and thorium C were compared with those of Henderson's curves and were found to be practically identical. Thus we were unable to find the cause of the discrepancy between other observers' values and ours.

† S. Rosenblum, 'C. R.,' vol. 188, p. 1401 (1929).

Velocity Considerations.

The ranges obtained may be considered in relation to the initial velocities of the α-particles as measured by Briggs and Laurence.* Assuming the law

$$V^3 = kR,$$

where V is the velocity and R the range, the ranges can be calculated from the velocities by taking the data for radium C′ as a basis of comparison. For the accuracy required in the values of the velocities, the differences between the values of Briggs and Laurence are negligible. The agreement of the observed ranges with the values calculated from the velocities is by no means exact as can be seen from fig. 3. In fig. 3 the differences between the observed ranges and the calculated ranges are plotted against the latter, the ranges of radium C′ being taken as unity. The difference curve appears to be of the same general form in each case, having a maximum negative value for short range thorium C α-particles.

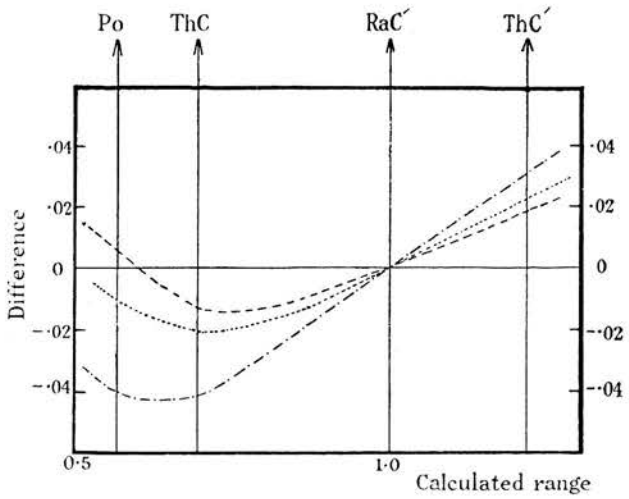

FIG. 3.—Difference between observed and calculated ranges plotted against calculated ranges.

..... Air, Oxygen and Nitrogen. ———— Argon. —·—·— Hydrogen.

Stopping Powers.

The stopping powers of the gases used relative to air and to argon are given in Table III. In figs. 4 and 5 these stopping powers are plotted against the cubes of the initial velocities.

* Briggs, 'Roy. Soc. Proc.,' A, vol. 114, p. 341 (1927); Laurence, 'Roy. Soc. Proc., A, vol. 122, p. 543 (1929).

Table III.

Stopping power = range in air/range in gas.

Source.	Air.	Oxygen.	Nitrogen.	Argon.	Hydrogen.
ThC′	1	1·060	0·993	0·958	0·211
RaC′	1	1·058	0·994	0·954	0·214
ThC	1	1·059	0·993	0·940	0·218
Po	1	1·062	0·993	0·929	0·224

Stopping power = range in argon/range in gas.

ThC′	1·044	1·110	1·037	1	0·220
RaC′	1·047	1·110	1·042	1	0·222
ThC	1·059	1·121	1·053	1	0·231
Po	1·076	1·145	1·071	1	0·241

Table IV gives the values obtained by other workers.

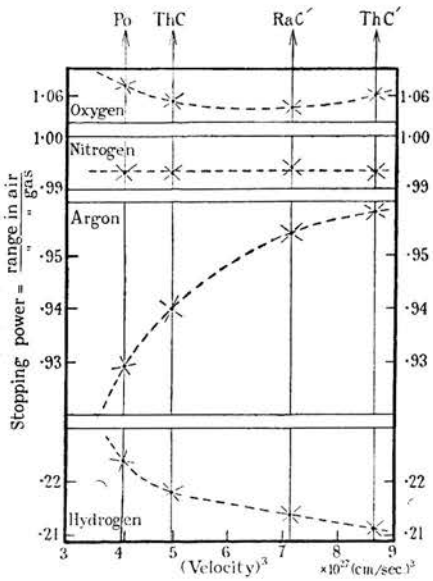

FIG. 4.

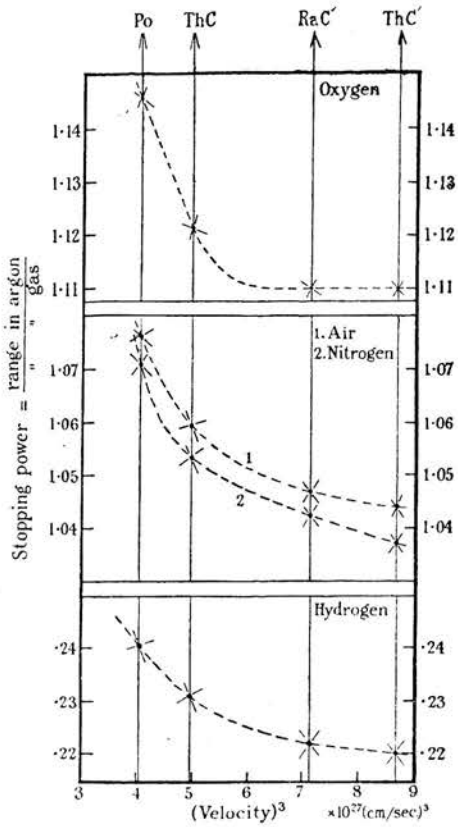

FIG. 5.

Table IV.

Stopping power = range in air/range in gas.

Observer.	Source.	Air.	Oxygen.	Nitrogen.	Argon.	Hydrogen.
Taylor	RaC′	1	1·11	—	—	0·224
Taylor	Po	1	1·10	—	—	0·224
van der Merwe	Po	1	1·06	0·99	—	0·26
Joliot and Onoda	Po	—	—	—	—	0·223
Onoda	Po	—	1·066	—	—	—

From fig. 5 it would appear that the stopping power relative to argon varies in the same way for all the gases examined.

Gurney, Gibson and Gardiner, and Gibson and Eyring* have measured the stopping powers of certain gases relative to air for different small portions of the ranges. Their experiments give the distance δx travelled by the α-particles in the gases used for a definite small decrease δE in the energy. Thus the stopping power σ of a gas relative to air is expressed as

$$\sigma = \frac{\delta x_{\text{air}}}{\delta E} \Big/ \frac{\delta x_{\text{gas}}}{\delta E}.$$

Whence

$$\frac{\delta x_{\text{gas}}}{\delta E} = \frac{\delta x_{\text{air}}}{\delta E} \times \frac{1}{\sigma}.$$

Assuming that extrapolated ranges R correspond to equal absorptions of energy E, this equation can be integrated :—

$$\int_0^E \frac{\delta x_{\text{gas}}}{\delta E} dE = \int_0^E \frac{\delta x_{\text{air}}}{\sigma \, \delta E} dE.$$

Therefore

$$R_{\text{gas}} = \int_0^{R\,\text{gas}} dx = \int_0^{R_{\text{air}}} \frac{dx}{\sigma}.$$

Hence by integrating the curves of $1/\sigma$ plotted against distance in air, the range in a gas can be calculated, assuming the values we have obtained in the case of air. This can only be done for the cases of hydrogen and argon and the values found are given in Table V together with the experimental results. The agreement is as good as can be expected from the data available.

* Gurney, ' Roy. Soc. Proc.,' A, vol. 107, p. 340 (1925) ; Gibson and Gardiner, ' Phys. Rev.,' vol. 30, p. 543 (1927) ; Gibson and Eyring, ' Phys. Rev.,' vol. 30, p. 553 (1927).

Table V.

Source.	Argon.		Hydrogen.	
	Observed.	Calculated.	Observed.	Calculated.
	cm.	cm.	cm.	cm.
ThC′	8·99	9·16	40·88	40·76
RaC′	7·27	7·44	32·74	32·72
ThC	5·00	5·10	21·61	21·44
Po	4·17	4·19	17·29	17·24

Gaunt's Theory of the Stopping Power of Hydrogen.

The stopping power of hydrogen atoms for α-particles has been calculated according to the new quantum mechanics by Gaunt* who obtains the formula :

$$-\frac{d\mathrm{T}}{dx} = \frac{4\pi \mathrm{N}\mathrm{E}^2\varepsilon^2}{\mu v^2}\log\frac{\gamma'\mu v^3}{2\pi\omega'\mathrm{E}\varepsilon},$$

where $-dT/dx$ is the rate of loss of energy for an α-particle of charge E and velocity v; N is the number of atoms per cubic centimetre and μ and ε are the mass and charge of an electron; ω' is the frequency of the head of the Lyman series and γ' is a constant equal to 1·02. This formula is the same as those previously obtained by Bohr and by Fowler† except in the value of the constant γ'. Gaunt considers that this equation will have the same *form* in the case of hydrogen molecules but that there is no reason to suppose that the constant γ', which is given in a very complicated way, will have the same value as for hydrogen atoms. By integration of this equation the range R is obtained as a function of the initial velocity v_0 :—

$$\int_0^{\mathrm{R}} dx = -\frac{m\mu}{4\pi \mathrm{N}\mathrm{E}^2\varepsilon^2}\int_{v_0}^{0}\frac{v^3\,dv}{\log\left(\gamma'\mu v^3/2\pi\omega'\mathrm{E}\varepsilon\right)},$$

where m is the mass of the α-particle. On making the substitution

$$u = -\tfrac{4}{3}\log\frac{\gamma'\mu v^3}{2\pi\omega'\mathrm{E}\varepsilon},$$

this equation reduces to

$$\mathrm{R} = \frac{m\mu}{12\pi \mathrm{N}\mathrm{E}^2\varepsilon^2\left(\gamma'\mu/2\pi\omega'\mathrm{E}\varepsilon\right)^{4/3}}\int_{\infty}^{-\frac{4}{3}\log\left(\gamma'\mu v_0^3/2\pi\omega'\mathrm{E}\varepsilon\right)}\frac{e^{-u}\,du}{u},$$

* 'Proc. Camb. Phil. Soc.,' vol. 23, p. 732 (1927).

† Bohr, 'Phil. Mag.,' vol. 44, p. 10 (1913); Fowler, 'Proc. Camb. Phil. Soc.' vol. 22, p. 793 (1925).

which can be evaluated. The ranges R for different values of v_0 were calculated using the values of the constants given in the ' Phys cal Review Supplement,' July, 1929, and the value 1·02 for γ' (or $3 \cdot 10 \cdot 10^{-16}$ for the value of the ratio of γ' to ω'). In order to compare the theoretical values for monatomic hydrogen with the observed values for molecular hydrogen, the calculated ranges were halved and are plotted in fig. 6. (Gaunt, in his calculations, uses

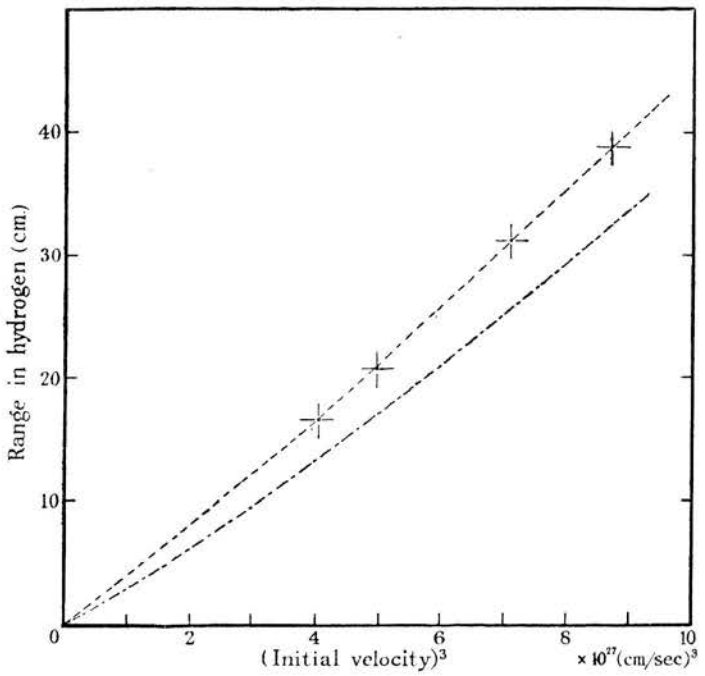

FIG. 6.

— · — · — Theoretical curve $\gamma'/\omega' = 3 \cdot 10 \cdot 10^{-16}$.
— — — — Theoretical curve $\gamma'/\omega' = 1 \cdot 20 \cdot 10^{-16}$.
+ + + Experimental values.

the same value of γ'/ω' as for atomic hydrogen although ω' should be proportional to the ionisation potential.) Clearly this modification of the formula does not give the correct values of the ranges in molecular hydrogen.

Assuming the form of the equation to be correct, the value of γ'/ω' was calculated from the known initial velocity and range of radium C′ and was found to be $(1 \cdot 20 \pm 0 \cdot 02) \times 10^{-16}$. Using this value of γ'/ω', a new theoretical curve was calculated and is shown in the upper curve of fig. 6. The experimental values lie on this curve with an accuracy well within the limits of experimental error. In his paper, Gaunt calculates the value of $(V_0^4 - V^4)/X$,

where V_0 and V are the velocities at the ends of a short interval of length X, and compares the result with Gurney's experimental value (*loc. cit.*) for the mean velocity $1{\cdot}98 \times 10^9$ cm. per second. Gurney's experimental value is $5{\cdot}4 \times 10^{35}$, Gaunt's calculated value, $6{\cdot}16 \times 10^{35}$, and the calculated value using our value of γ'/ω', $5{\cdot}39 \times 10^{35}$. The theo y of Gaunt for hydrogen atoms can therefore be extended to the case of molecular hydrogen if a new value of the ratio of γ' to ω' equal to $(1{\cdot}20 \pm 0{\cdot}02) \times 10^{-16}$ is used. The calculated values of both stopping powers and ranges agree with the observed values within the limits of experimental error.

γ' may be calculated by assuming a value for the ionisation potential of molecular hydrogen. Gaunt's theory gives no indication as to which value of this quantity should be used, and there are considerable variations in the values obtained both theoretically and experimentally. Assuming the value 15·3 volts obtained from the spectroscopic data of the International Critical Tables, we deduce the value 0·446 for γ', but whatever value of the ionisation potential is adopted, the value of γ' obtained is much less than the value for atomic hydrogen. Thus although the expression for the rate of loss of energy remains of the same form in molecular hydrogen, γ' and ω' both alter. Had γ' remained unaltered, then the rate of loss of energy would have been the same in molecular hydrogen as in atomic hydrogen except for the difference brought about by their different ionisation potentials, but since γ' is less, it appears that the processes controlling the rate of loss of energy of an α-particle are less effective in molecular hydrogen.

Summary.

The ranges of α-particles of different initial velocities have been measured in certain ga es and the stopping powers of these gases obtained. The gases used were air, oxygen, nitrogen, argon and hydrogen. The results for polonium are in agreement with those of Curie, Joliot and Onoda, and Onoda. In the case of argon and hydrogen the ranges agree with those calculated from the stopping powers obtained by Gurney. The relation between ranges and initial velocities is discussed. Finally, it is shown that the theory of Gaunt for the stopping power of hydrogen atoms can be extended to the case of molecular hydrogen.

In conclusion we wish to express our thanks to Sir Ernest Rutherford for his interest throughout this work, and to Dr. Chadwick for his advice and help. We further wish to thank Dr. Chadwick and Mr. Crowe for the preparation of the radioactive sources.

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31/5/31